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UK Plastic
Composite Propellant
Paper by Peter Penny
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Work started in 1930's at Woolwich by a team headed by (Sir) Alwyn Crow. It had, at first, relatively low priority. Cordite propellant work began in 1934 whilst research into plastic propellant (comprising an inorganic oxidiser combined with an uncured polymeric binder) started a year later in 1935. At around this time work was also carried out on a series of cast formulations containing Ammonium Nitrate

The search for case bondable propellants was initially based on a NC/NG matrix plus a non reactive hydrocarbon binder such as polystyrene combined with a sodium nitrate oxidiser and was as such strictly a composite modified double base propellant.

The main thrust of the work was concerned with true double base propellants. In 1936 Crow's team at Woolwich were developing a 2in Cordite rocket to match the performance of the 3in AA gun and it wasn't until 1938 that true composite formulations containing ammonium perchorate with a polymeric binder were fired over a range of temperatures reaching as low as -15C.

Early in World War II Crow's work on true composites was given increased importance when government fears were expressed regarding the lack of material supplies particularly cellulose for the nitrocellulose used in cordite propellants for both guns and rockets.

The search for alternative case bondable propellants was therefore based on entirely different materials to Cordites. Suitable oxidisers were difficult to find. Salts of potassium, sodium or lithium gave smoky exhausts and low performance, whilst ammonium nitrate although cheap and readily available was hygroscopic, and exhibited a phase change at 32C that precluded its use at that time.

Ammonium Perchlorate (AP), however, combined with polyisobutene (PIB), possessed good low temperature properties with a firing limit found to be as low as -40C. In 1938 the production of Plastic Propellant began. Motors from 1" to 35" diameter were eventually produced in large numbers using this basic propellant mixture.

So during the formative years of composite propellant development Britain concentrated almost entirely upon the AP/PIB mixture. This had the physical properties similar to plasticene and was known as "Plastic Propellant". The physical properties of this type of propellant restricted its use to, by today's standards, relatively small diameter motors not exceeding 2m in diameter.

As will be seen later in the presentation, the US propellant chemists followed another, quite different route that led eventually to the rubbery, cross linked polymeric propellant in use today. This, unlike plastic propellant, could be used over a very wide temperature range and at very large motor diameters.

This happy state of affairs was not reached for some considerable time so that composite propellants did not play a significant part in the battles of World War II.

In fact Technical Note No RPD 44 prepared by M Goyer in January of 1951 (Secret – Discrete at the time but now de-classified), which considered both liquid & solid propellants, came to the conclusion that there were no British solid propellants available which could adequately cover the range from -50 to +60C.

The propellant in use at that time was the cordite SU/K which in itself had problems; most especially brittleness at low temperatures, low values of Young's modulus at high temperatures, large variation in performance with change in temperature as well as an inability to withstand high temperature storage.

Miss Goyer was not completely without hope in that she thought that *"Defects may be considerably reduced by the use of Colloidal & Plastic Propellants"*. A prediction which was subsequentially proved correct.

Her summary of the then present state of propellant development is summarised in the table below:-

	EDB & CDB SU/K Non Platonised	Plastic RD 2043 Sodium Nitrate/AP To be replaced by RD 2201 AP	US Composite
Temp Limits	-40 to +50	-50 to +50	-50 to +70 Claimed
Reproducibility of Ballistics	Fairly Good Exponent 0.5 - 0.8	Poor - Oxidant Particle Size Exponent 0.3 to 0.7	Not Known Exponent 0.4 to 0.5
Other Penalties		Smoke & Fumes More work needed on PIB	Extensive trials required
Low Temps	Brittle Rough Handling	Good	Good Bonding & Cracking
High Temp Storage	Short storage Life	Improved Storage Life	Long Storage Life
Material	No Problems Raw Materials Imported	Sodium Nitrate ok Amm Perc supply restricted	Not Available in UK
Remarks	High SI Some success with Platonisation	Sodium Nitrate – Low SI & Very Smokey AP – high SI but has "Secondary Peaks" Possibility of Platonised Propellant	Promising for Very Large Motors

What is interesting to note is the possibility of platonised plastic propellant. This was never achieved.

By 1953 the only solid propellant sustainer that promised anywhere near the performance required to replace the existing liquid propellant systems was Ratcatcher which first flew in January 1953 in an English Electric D4 (Red Shoes) airframe. Ratcatcher originally used pressed charges of Ammonium Nitrate (~12%), Guanodine Nitrate (~85%) and Potassium Nitrate (~1%).

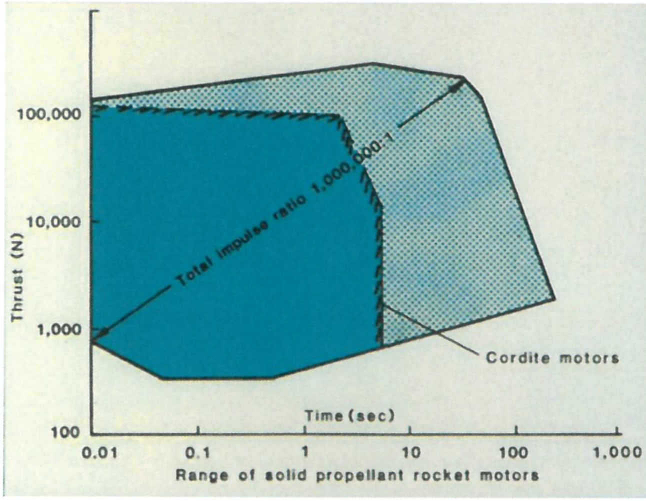
These charges, known as "cheeses" because of their colour and shape, were loaded loosely into the motor case and held in place by springs. An attempt to improve the temperature capability of the charges was made by removing the Guanodine Nitrate, increasing the Ammonium Nitrate content to ~ 77%, increasing the Potassium Nitrate content to ~9% and adding ~11% of Hycar, an elasomeric compound, into the propellant.

However even this formulation was still low on performance and the inability of the pressed charges to withstand the required operating and staorage temperature range led to Ratcatcher being cancelled after the D4 programme for Red Shoes being replaced by the Westcott Smokey Joe motor.

The Red Shoe programme went through a long series of test vehicles and eventually evolved into the well known Thunderbird missile which used Westcott Plastic Propellant motors for both boost and sustain.

During the 1950s and 60s, solid fuel rocket motors were developed for a variety of purposes at the Rocket Propulsion Establishment (R.P.E.) at Westcott in Buckinghamshire.

The motors, named after British birds, were developed for a variety of different uses. Some were used for testing 'off the shelf' designs for various specific purposes. Most were associated with the development and production of guided weapons, principally surface to air missiles. However, a highly successful sounding rocket, Skylark, was also developed, which was fired in the hundreds, and came in a variety of different configurations.



So, by the late 1960's plastic propellant had been developed to such an extent that motors containing plastic propellant covered a much wider range of operating requirements than it's double base rival with total impulses (thrust x burning time) of 11Ns to 9.5MNs covering a ratio of just under a million to one.

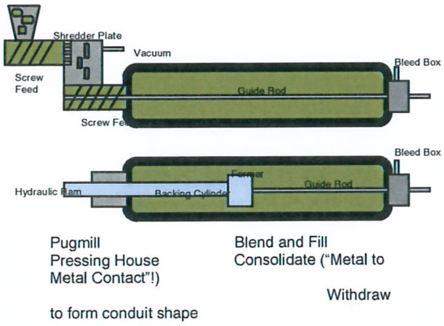
The motors using plastic propellant covered diameters ranging from 22mm to 1370mm and had burning times ranging from a few milliseconds to 300 seconds, a ratio of 20,000 to 1.

Perhaps one of the "unsung heroes" of the Westcott motors was the 5inch Light Alloy Projectile (5" LAP). It's design produced a motor of such a high volumetric loading density, low cost and reliability that it has been used as the basis of many motor designs and is still in use as a boost motor for sled tracks.

Plastic propellant typically comprised:-

Ammonium Perchlorate	50%	
White crystalline inorganic oxidiser		
Ammonium Picrate	20%	
To depress the burning rate		
Aluminium	15%	
Spheroidal Powder		
Binder Comprising: -	15%	
Polybutene		*(Fuel ~90%)*
Ethyl Oleate		*(Plasticiser ~4%)*
Pentaerythritol Dioleate		*(Mixing Aid ~3%)*
Sodium di-2-ethyl hexyl Sulphosuccinate		*(Wetting Agent ~3%)*
Ballistic Modifier	~1%	
Metal Salt or Oxide of Transition Metal Group		
E.g. Ti O2, CuCr, Oxamide		

The propellant mixed at ERDE Waltham Abbey or ROF Bridgewater and the motors filled at RPE Westcott or ROF Bridgewater.



The mixing took place in modified bread dough mixer. The Baker Perkins mixers were of a "planetary" design with a figure of 8 bowl in which the mixing blades rotated around each other. Mixing took place for about 3 hours, although some of the author's work as a sandwich course student examined the effects of mixing times as low as 1 hour up to as long as 8 hours.

After mixing the propellant was transported to the Pug mill, were the motor was initially filled and then to the pressing house, where the internal conduit charge shape was formed.

The pug mill was, in effect, a large mincer. The plastic propellant was added to a conveyer belt which transported the rugby ball sized portions of propellant through a flame and explosion proof trap to the top hopper of the Pugmill. Beneath the hopper was a screw feed into which the propellant dropped. The screw feed forced the propellant through a shredder plate. The strands of propellant then dropped into a second screw feed.

The propellant in the shredder plate formed a vacuum seal so that air could be evacuated from the whole of the second screw feed and motor case.

Blending of propellant was necessary for motors used in pairs or greater numbers on a single launch vehicle. For these applications the burning rate of each motor was required to be as close as possible. Plastic propellant was ideal for this since chunks of propellant from a number of different batches could be placed in the top hopper and blended propellant collected from the bottom screw feed.

Once the propellant was properly blended the motor filling could commence. Once again rugby sized pieces of propellant would be dropped into the top hopper and the vacuum applied. For motor filling, the empty motor case, already prepared with its lining and a layer of black Bostik adhesive around the inside, would be attached to the bottom screw feed and held securely in place by means of a tie rod. The propellant would be forced into the case until it began to emerge from a bleed hole at the far end of the motor.

The propellant could therefore be bonded to the motor case. This capability had enormous advantages from a performance point of view since most rocket motors are constrained by volume as well as mass. Double base motors at that time were cartridge loaded, that is to say they were loose inside the case. Their operation depended upon the ability of the combustion gases to be able to flow around the outside of the charge so as to equalise the pressure across the charge web. This meant that a relatively large gap had to be left between the charge and the case wall. In addition to this both case and internal burning charges had to be lined to protect them from the hot combustion gases. This arrangement wasted a significant amount of the available cross section.

The filled motor was then moved to the pressing house. Again this comprised two rooms separated by a blast resistant wall. The motor was attached to a backing cylinder which housed a hydraulic ram that protruded through from the control room which housed the pressing staff.

The backing cylinder had attached to its forward end a former which would determine the shape of the internal conduit of the charge.

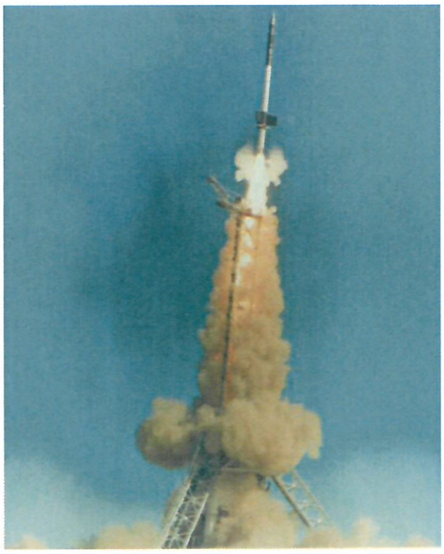
The former was pushed through the propellant by the hydraulic ram forcing propellant out of the bleed hole at the forward end of the motor. At some predetermined point the bleed hole was closed and the former advanced until a set position was reached. This pressurisation of the propellant, know as consolidation, pushed the charge hard against the sides of the case and close any vacuoles that had been formed during the filling process on the pug mill. The former was then withdrawn slowly thus forming a constant cross section of the shape desired by the rocket motor designers.

Examples of such motors are shown below:-

Motor	Tb	Mean Thrust	Isp	Mp	Propellant	
Bantam IV	33.6	1.7	2197	23.6	RD 2423/4	
Blackbird 2a	1.7	15.6	1844	15.0	RD S1069	
Chick 2a	0.2	20.9	2158	2.0	RD 2423	Petrel & Skua
Fieldfare	6.4	5.0	1707	201.6	RD 2413	Flight test vehicle
Goose 2	16.0	22.0	1903	207.9	RD 2415	Flight test vehicle
Goose 3	4.1	88.9	2138	182.1	S 1046	
Gosling 1k	2.5	104.0	1952	142.0	PU	
Gosling 4e	3.2	127.0	2236	190.0	RD 2410	Red Duster, Leo
Gosling 5a	2.5	107.0	1982	145.0	PU	
Gosling 15 a/b	3.3	124.0	2344	187.0	RD 2421	Bloodhound
Heron	3.2	127.0	2236	190.0	RD 2419	Inter 300, Fulmar & Flamenco Sounding Rockets
Lapwing	30.6	5.0	2335	65.7	RD 2431/2424	Torch
Linnet CTPB	3.2	23.3	2320	36.9	RD CTPB	Alarm test vehicle
Lobster 1a	1.5	32.0	2276	25.8	RD 2304	
Lobster 2a	1.1	30.7	2119	17.2	RD 2311	
Lobster 5a	2.5	26.7	2335	31.2	S 1010	
Pendine Boost	1.0	35.0	2026	17.4	RD 2304	Foil
Pipit 2	0.5	104.0	2433	42.8	RD 2428	
Pipit 9	0.6	106.0	2472	42.8	E 4255	Pipit X used for Rayo Demonstrator
Rook 3	5.5	326.0	2256	869.7	RD 2410	Hyperion, Ranger
Rook V V	6.7	297.0	2394	887.9	S 1017	
Siskin 2	3.5	5.8	2747	7.7	S 1066	
Snipe	15.8	15.0	1913	135.4	RD 2437	
Starling 2a	3.3	10.7	1923	20.1	RD 2424	
Stonechat	37.0	240.0	2080	4322.0	RD 2430	Spacelark
Thrush 1a	1.7	19.3	1982	18.8	RD 2434	Squid
Thrush 2a	1.5	21.3	2011	18.8	RD 2425	
Waxwing	55.0	155.7	2766	313.5	RD 2435	

Perhaps the most successful of vehicles designed to use plastic propellant motors was the Skylark series.

The programme was originated in 1955 with a planned mission to lift 45kg to 100km.
The main launch motor was Raven with a total impulse of 1780Ns/kg, a burn time of 30secs and a propellant mass of 1000kg.



The vehicle was first launched at Woomera in 1957. A Cuckoo booster motor was added in 1960 which provided an extra 80kN thrust for 4secs.

An even later addition was the Goldfinch motor which contained some very powerful plastic propellant and which; incidentally, blew up and destroyed the pug mill during my tenure as Assistant Director, Propulsion!

The combination of Raven XI plus Goldfinch would lift 100kg to 500km.

The 400th Skylark was memorable. The Kiruna launch site was filled with journalists, the champagne was on ice and the vehicle was ready.

Unfortunately the Raven motor burnt through its hypalon insulation and the mission was a complete failure. I got the news as I was leaving the house for our children's junior school fete where we were running the book stall. Instead of attending the fete, I spend the weekend trawling through motor specifications trying to find what had caused the problem. It turned out that a "minor" change had been made to the hypalon liner such that it failed in flight. The problem was fixed and Skylark went on to a further 41 successful, launches.

The rocket which made its maiden launch in 1957 from Woomera, Australia, had been used to take a huge range of scientific experiments into space.

On the 2nd May 2005 at 0700 BST in Sweden the 441st and final Skylark blasted up over the Swedish Space Corporation's Esrange site, near Kiruna.

The final mission, called Maser 10, was organised under the European Space Agency banner and carried five experiments

Over the years Skylark has taken on and had proposed numerous configurations, some of which had orbital capability.

Some of the motors used or proposed for Skylark missions are shown below:-

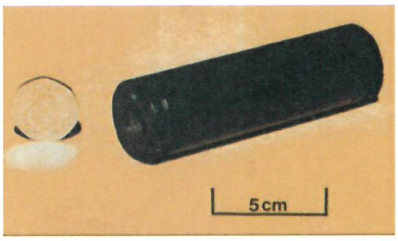
Motor	Burn Time (s)	Thrust (kN)	Length (mm)	Propellant Mass (kg)
Cuckoo I	4.1	81	550	180
Cuckoo II & IV	10.0	36	1316	189
Goldfinch IIa	2.7	182	2224	311
Gosling IVe	3.2	127	3442	190
Gosling XV	3.3	124	3439	187
Raven VI	30.0	67	5232	974
Raven VIII	30.0	45	5207	843
Raven XI	30.0	80	5156	1019
Stonechat II	37.0	240	5486	4322

In the UK, plastic, non cross linked, propellant motors were developed whilst in the USA rigid and flexible rubbery, cross linked, propellants were developed. Plastic propellant motors were cheap, easy to manufacture and easy to repress. Changes to the charge design could easily be made by simply refilling and/or repressing the motor. The motors were also available immediately following pressing, requiring no lengthy curing time as did their rubbery US equivalents. However plastic propellants suffered from one major drawback – They were size limited. Beyond a critical diameter, dependent upon the storage and/or operating temperature regime the propellant would slump under its own weight. The US cross linked rubbery propellants suffered no such limitation. However the UK were not at that time concerned with very large solid motors. They were covered by liquid propelled rocket engines so that a wide range and large numbers of UK plastic propellant motors were produced.

Stonechat
The UK's Largest Plastic Propellant Motor

	Smallest (Imp)	Largest (Stonechat
Charge Mass	30g	4300kg
Diameter	10mm	1000mm
Thrust	0.8kN	240kN
Burn Time	0.07s	40s

Motor	Lowest	Highest
Burn Time	Imp XVIc 0.013s	Waxwing 55s
Thrust	Imp VIIIa, Imp XV 356N	Rook III 326kN
Total Impulse	Imp Ia 11Ns	Stonechat II 9500KNs



The smallest motors were called Imps. They were used for a wide variety of tasks, for example, to induce flutter on experimental aircraft wings.

RPE Westcott had at that time a wide range of test sites that could accept motors with thrusts of up to 1.78MN. It also had vertical firing sites, vacuum firing facilities as well as a centrifuge and a radio attenuation firing site.

Here is a Stonechat firing in K2 Site with its explosive limit of 9090kg

Prior to firing or delivery the motors would be subjected to stringent non destructive testing. During development RPE could use its own shock, drop and pressure cycling facilities. It also had the full range of environmental test chambers available with temperature ranges from -55C to +90C as well as dynamic balancing facilities for spun motors. All this was backed up by the superb design and development teams as well as state of the art manufacturing workshops.